# OpenMP Loop Parallelism (2A)

- Loop
-

Please send corrections (or suggestions) to youngwlim@hotmail.com.

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# Parallel region

the **parallel** pragma :
creates parallelism in OpenMP codes

a **parallel region** :
- a block preceded by the omp **parallel** pragma
- executed by a newly created team of **threads**.

```
#pragma omp parallel
{
  // this is executed by a team of threads
}
```

this is an instance of the **SPMD** model:
all **threads** execute the same segment of code.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# Master thread and a team of threads

Immediately preceding the **parallel block**,
one **thread** will be executing the code.

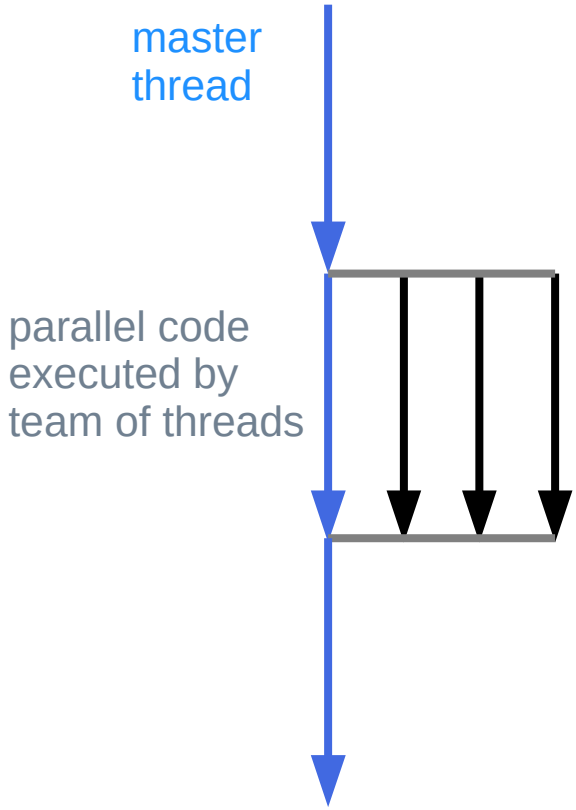
In the **main** program this is the **initial thread**.

At the start of the block, a new team of **threads** is created,
and the **thread** that was active before the block becomes
the **master thread** of that team.

After the block, only the **master thread** is active.

Inside the block there is **team** of **threads**:

each **thread** in the **team**
- executes the body of the block,
- can access all variables of the surrounding environment.




https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# Shared / Private data and thread number

the **threads** that are forked are
all **copies** of the **master thread** :

**shared data** :
they have access to all that was computed so far;

each thread can also have **private data**,

each thread can identify themselves:
**thread number**.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# Thread number function

**omp_get_thread_num()** :
to find out which thread you are
and to execute work that is individual to that thread.

**omp_get_num_threads()**
to find out the total number of threads.

these functions give a number
relative to the current team

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# Distributing the work over the threads

In a **team** of **threads**,
initially there will be replicated execution;

a **work sharing construct** divides
available parallelism over the threads.

OpenMP uses **teams** of **threads**,
and inside a **parallel region**
the **work** is distributed over the **threads**
with a **work sharing construct**.

**threads** can access **shared data**,
and they have some **private data**.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# Work Sharing Constructs

**sections** Construct – structured block

**single** Construct – only one of the threads

**workshare** Construct – a separate units of work

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# **sections** construct

- a non-iterative worksharing construct
- contains a set of structured blocks

- each structured block
  - are distributed among threads in a team
  - executed once by one of the threads in a team
  - in the context of its implicit task.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# **single** construct

- the specified structured block is executed
  - by only one of the threads in the team
  - in the context of its implicit task.

- The executing thread need not be the master thread

- the other threads in the team
  - do not execute the block
  - wait at an implicit barrier at the end of the **single** construct unless a **nowait** clause is specified.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# **workshare** construct

- divides the execution of
  the enclosed structured block
  into separate units of work

- causes the threads of the team
  to share the work

- each unit is executed
  only once by one thread,
  in the context of its implicit task.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# **sections** construct

#pragma omp **sections** [clause[ [,] clause] ... ] *new-line*
{
[#pragma omp section *new-line*]
*structured-block*
[#pragma omp section *new-line*
*structured-block*]
...
}

where clause is one of the following:

**private**(list)
**firstprivate**(list)
**lastprivate**([ lastprivate-modifier:] list)
**reduction**([reduction-modifier ,] reduction-identifier : list)
**allocate**([allocator :] list)
**nowait**

https://www.openmp.org/spec-html/5.0/openmpsu37.html#x59-1010002.8.1

# **section** construct

#pragma omp **sections** [clause[ [,] clause] ... ] *new-line*
{
[#pragma omp **section** *new-line*]
*structured-block*
[#pragma omp **section** *new-line*
*structured-block*]
...
}

When program execution reaches a **omp sections** directive,
program segments defined by the following **omp section** directive
are distributed for parallel execution among available threads.

A barrier is implicitly defined at the end of the larger program region
associated with the **omp sections** directive unless the nowait clause is specified.

https://www.openmp.org/spec-html/5.0/openmpsu37.html#x59-1010002.8.1

# **single** construct

#pragma omp **single** [clause[ [,] clause] ... ] *new-line*
*structured-block*

where clause is one of the following:

**private**(list)
**firstprivate**(list)
**copyprivate**(list)
**allocate**([allocator :] list)
**nowait**

https://www.openmp.org/spec-html/5.0/openmpsu38.html#x60-1090002.8.2

# **workshare** construct

A worksharing directive (!) which allows parallelisation of Fortran 90 array operations, WHERE and FORALL constructs.

```
!$omp workshare
    structured-block
!$omp end workshare [nowait]
```

https://www.openmp.org/spec-html/5.0/openmpsu39.html#x61-1170002.8.3

# **for** construct

#pragma omp **for** [clause ...]  newline

**schedule** (type [,chunk])
**ordered**
**private** (list)
**firstprivate** (list)
**lastprivate** (list)
**shared** (list)
**reduction** (operator: list)
**collapse** (n)
**nowait**

for_loop

https://hpc.llnl.gov/openmp-tutorial#WorkSharing

# Clauses (1)

**private** (list)

Declares the scope of the data variables in list
to be **private** to each thread.
Data variables in list are separated by commas.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (2)

**firstprivate** (list)

Declares the scope of the data variables in list
to be **private** to each thread.
Each new private object is initialized
as if there was an implied declaration within the statement block.
Data variables in list are separated by commas.

**lastprivate** (list)

Declares the scope of the data variables in list
to be **private** to each thread.
The final value of each variable in list, if assigned,
will be the value assigned to that variable in the last section.
Variables not assigned a value will have an indeterminate value.
Data variables in list are separated by commas.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (3)

**copyprivate** (list)

broadcasts the values of variables specified in list
from one thread of the team to other threads

This occurs after the execution of the structured block
associated with the omp single directive,
and before any of the threads leave
the barrier at the end of the construct.

For all other threads in the team,
each variable in the list becomes defined
with the value of the corresponding variable
in the thread that executed the structured block.

Data variables in list are separated by commas.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (4)

**reduction** (operator: list)

Performs a **reduction** on all **scalar variables** in list
using the specified **operator**.
Reduction variables in list are separated by commas.

A **private copy** of each variable in list is created for each thread.

At the end of the statement block,
the **final** values of all **private copies** of the reduction variable
are combined in a manner appropriate to the **operator**,
and the **result** is placed back in the **original value**
of the **shared reduction variable**.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (5)

**reduction** (operator: list)

For example, when the **max operator** is specified,
the original reduction variable value combines
with the final **values** of the **private copies**
by using the following expression:

```
original_reduction_variable =
    original_reduction_variable  < private_copy
                                 ? private_copy
                                 : original_reduction_variable;
```

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (6)

**nowait**

Use this clause to avoid the **implied barrier**
at the end of the **sections** directive.

This is useful if you have multiple independent
**work-sharing sections** within a given parallel region.

Only one **nowait** clause can appear
on a given **sections** directive.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (7)

**collapse** (**n**)

allows you to parallelize multiple loops in a nest
without introducing nested parallelism.

Only one **collapse** clause is allowed
on a worksharing **for** or **parallel for** pragma.

**n** : the number of nested loops to be parallelized

the specified number of loops must be present lexically.
that is, none of the loops can be in a called subroutine.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (8)

The loops must form a rectangular iteration space and
the bounds and stride of each loop
must be invariant over all the loops.

If the loop indices are of different size,
the index with the largest size
will be used for the collapsed loop.

The loops must be perfectly nested;
that is, there is no intervening code
nor any OpenMP pragma
between the loops which are collapsed.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (9)

The associated do-loops must be structured blocks.
Their execution must not be terminated by an break statement.

If multiple loops are associated to the loop construct,
only an iteration of the innermost associated loop
may be curtailed by a continue statement.

If multiple loops are associated to the loop construct,
there must be no branches to any of the loop termination statements
except for the innermost associated loop.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Collapse example (1)

The **collapse** clause is used to convert a prefect nested loop into a single loop then parallelize it.

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
    #pragma omp parallel for
    for (int i = 0; i < 4; i++)
    {
        for (int j = 0; j < 5; j++)
        {
            printf("Thread number is %d\n", omp_get_thread_num());
        }
    }

    return 0;
}
```

```
# gcc -fopenmp parallel.c
# ./a.out
Thread number is 0
Thread number is 0
Thread number is 0
Thread number is 0
Thread number is 0
Thread number is 3
Thread number is 3
Thread number is 3
Thread number is 3
Thread number is 3
Thread number is 1
Thread number is 1
Thread number is 1
Thread number is 1
Thread number is 1
Thread number is 2
Thread number is 2
Thread number is 2
Thread number is 2
Thread number is 2
```

https://nanxiao.gitbooks.io/openmp-little-book/content/posts/collapse-clause.html?q=

# Collapse example (2)

Every iteration of outer loop will be dispatched to one thread to run:

```
#pragma omp parallel for
for (int i = 0; i < 4; i++)
{
    for (int j = 0; j < 5; j++)
    {
        printf("Thread number is %d\n", omp_get_thread_num());
    }
}
```

Each thread will execute the inner loop sequentially:

So there are only 4 threads in active state actually.

https://nanxiao.gitbooks.io/openmp-little-book/content/posts/collapse-clause.html?q=

# Collapse example (3)

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
   #pragma omp parallel for  collapse(2)
   for (int i = 0; i < 4; i++)
   {
      for (int j = 0; j < 5; j++)
      {
         printf("Thread number is %d\n", omp_get_thread_num());
      }
   }

   return 0;
}
```

```
# gcc -fopenmp parallel.c
# ./a.out
Thread number is 0
Thread number is 2
Thread number is 18
Thread number is 16
Thread number is 6
Thread number is 8
Thread number is 7
Thread number is 10
Thread number is 14
Thread number is 12
Thread number is 13
Thread number is 17
Thread number is 15
Thread number is 9
Thread number is 11
Thread number is 19
Thread number is 4
Thread number is 3
Thread number is 5
Thread number is 1
```

https://nanxiao.gitbooks.io/openmp-little-book/content/posts/collapse-clause.html?q=

# Collapse example (4)

This time we can see 20 threads are utilized.

The integer argument of **collapse** (i.e., 2 in this example) identifies
how many loops to be parallelized,
and counted from outer side to inner side

Please be aware that **collapse(1)** and no collapse
take the same effect for loop parallelism

https://nanxiao.gitbooks.io/openmp-little-book/content/posts/collapse-clause.html?q=

# Clauses (10)

Use the OpenMP **collapse** clause
to increase the total number of iterations
that will be partitioned across the available number of OMP threads
by reducing the granularity of work to be done by each thread.

If the amount of work to be done by each thread
is non-trivial (after collapsing is applied),
this may improve the parallel scalability of the OMP application.

https://software.intel.com/content/www/us/en/develop/articles/openmp-loop-collapse-directive.html

# Clauses (11)

You can improve performance by avoiding
use of the collapsed-loop indices (if possible)
inside the collapse loop-nest

since the compiler has to recreate them
from the collapsed loop-indices
using divide/mod operations AND

the uses are complicated enough
that they don't get dead-code-eliminated
as part of compiler optimizations

https://software.intel.com/content/www/us/en/develop/articles/openmp-loop-collapse-directive.html

# Clauses (12)

```
#pragma omp parallel for collapse(2)
  for (i = 0; i < imax; i++) {
    for (j = 0; j < jmax; j++) a[ j + jmax*i] = 1.;
  }
```

Modified example for better performance:

```
#pragma omp parallel for collapse(2)
  for (i = 0; i < imax; i++) {
     for (j = 0; j < jmax; j++) a[ k++] = 1.;
  }
```

https://software.intel.com/content/www/us/en/develop/articles/openmp-loop-collapse-directive.html

# Clauses (13)

**Ordered**

During execution of an iteration of a loop or a loop nest within a loop region, the executing thread must not execute more than one ordered region which binds to the same loop region. As a consequence, if multiple loops are associated to the loop construct by a collapse clause, the ordered construct has to be located inside all associated loops.

Specify this clause if an ordered construct is present within the dynamic extent of the omp for directive.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (14)

**schedule** (type)

Specifies how iterations of the for loop are divided among available threads. Acceptable values for type are:

**auto**

With auto, scheduling is delegated to the compiler and runtime system. The compiler and runtime system can choose any possible mapping of iterations to threads (including all possible valid schedules) and these may be different in different loops.

**dynamic**

Iterations of a loop are divided into chunks of size ceiling(number_of_iterations/number_of_threads).

Chunks are dynamically assigned to active threads on a "first-come, first-do" basis until all work has been assigned.

**dynamic,n**

As above, except chunks are set to size n. n must be an integral assignment expression of value 1 or greater.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (15)

**guided**

Chunks are made progressively smaller until the default minimum chunk size is reached. The first chunk is of size ceiling(number_of_iterations/number_of_threads). Remaining chunks are of size ceiling(number_of_iterations_left/number_of_threads).

The minimum chunk size is 1.

Chunks are assigned to active threads on a "first-come, first-do" basis until all work has been assigned.

**guided,n**

As above, except the minimum chunk size is set to n; n must be an integral assignment expression of value 1 or greater.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Clauses (16)

**runtime**

Scheduling policy is determined at run time. Use the OMP_SCHEDULE environment variable to set the scheduling type and chunk size.

**static**

Iterations of a loop are divided into chunks of size ceiling(number_of_iterations/number_of_threads). Each thread is assigned a separate chunk.

This scheduling policy is also known as block scheduling.

**static,n**

Iterations of a loop are divided into chunks of size n. Each chunk is assigned to a thread in round-robin fashion.

n must be an integral assignment expression of value 1 or greater.

This scheduling policy is also known as block cyclic scheduling.

https://www.ibm.com/docs/en/xl-c-aix/13.1.2?topic=processing-pragma-omp-section-pragma-omp-sections

# Parallel region

An important difference between **OpenMP** and **MPI** is
that parallelism in **OpenMP** is **dynamically activated**
by a **thread spawning** a **team** of **threads**.

Furthermore, the **number** of **threads** used
can differ between **parallel regions**,
and **threads** can create **threads** recursively.

This is known as as **dynamic mode** .

By contrast, in an **MPI** program
the **number** of running processes is
(mostly) constant throughout the run,
and determined by factors external to the program.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-parallel.html

# Loop parallelism

OpenMP parallel loops are an example of
OpenMP `worksharing' constructs

take an amount of work and
distribute it over the available threads
in a parallel region.

The parallel execution of a loop
can be handled a number of different ways.

For instance, you can create
a parallel region around the loop,
and adjust the **loop bounds**:

```
#pragma omp parallel
{
  int threadnum = omp_get_thread_num(),
      numthreads = omp_get_num_threads();

  int low = N*threadnum/numthreads,
      high = N*(threadnum+1)/numthreads;

  for (i=low; i<high; i++)
    // do something with i
}
```

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop parallelism

use the **parallel for** pragma:

```
#pragma omp parallel
#pragma omp for
for (i=0; i<N; i++) {
  // do something with i
}
```

you don't have to calculate
the loop bounds for the threads yourself,

but you can also tell OpenMP
to assign the loop iterations
according to different schedules

```
#pragma omp parallel
{
   code1();
   #pragma omp for
   for (i=1; i<=4*N; i++) {
      code2();
   }
   code3();
}
```

The code before and after the loop is
executed identically in each thread; t

he loop iterations are spread
over the four threads.

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop parallelism

#pragma omp parallel spawns a group of threads, while #pragma omp for divides loop iterations between the spawned threads. You can do both things at once with the fused #pragma omp parallel for directive.

#pragma omp for only delegates portions of the loop for different threads in the current team. A team is the group of threads executing the program. At program start, the team consists only of a single member: the master thread that runs the program.

To create a new team of threads, you need to specify the parallel keyword. It can be specified in the surrounding context:

```
#pragma omp parallel
{
  #pragma omp for
  for(int n = 0; n < 10; ++n)
  printf(" %d", n);
}
```

https://stackoverflow.com/questions/1448318/omp-parallel-vs-omp-parallel-for

# Loop parallelism

The difference between parallel, parallel for and for is as follows:

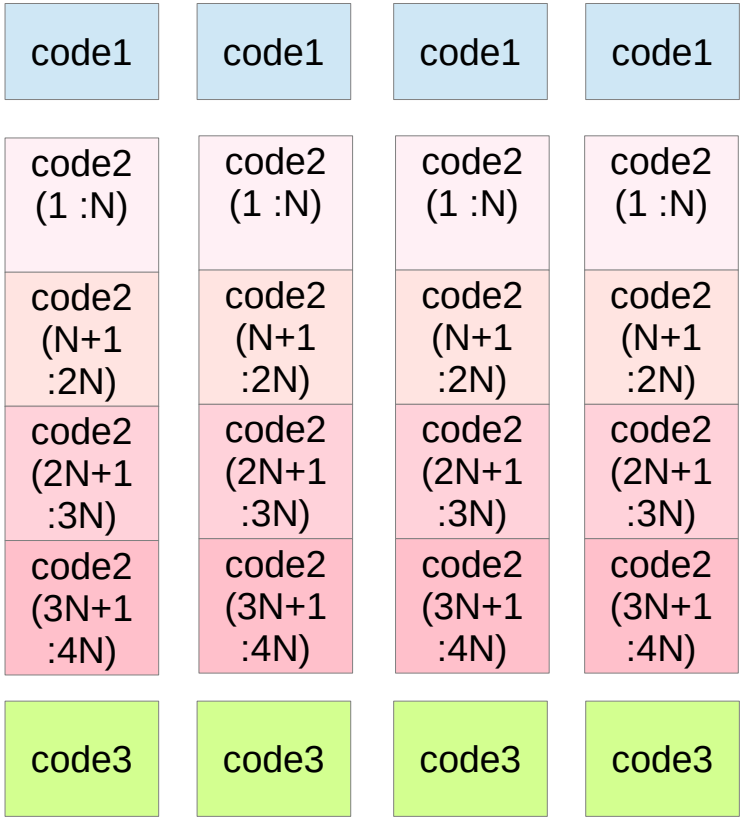
A team is the group of threads that execute currently. At the program beginning, the team consists of a single thread. A parallel construct splits the current thread into a new team of threads for the duration of the next block/statement, after which the team merges back into one. for divides the work of the for-loop among the threads of the current team.

It does not create threads, it only divides the work amongst the threads of the currently executing team. parallel for is a shorthand for two commands at once: parallel and for. Parallel creates a new team, and for splits that team to handle different portions of the loop. If your program never contains a parallel construct, there is never more than one thread; the master thread that starts the program and runs it, as in non-threading programs.

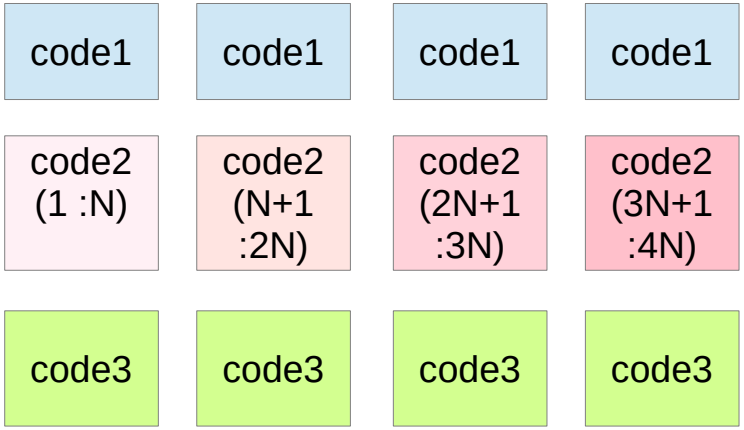
https://stackoverflow.com/questions/1448318/omp-parallel-vs-omp-parallel-for

# Loop parallelism

Without #pragma omp **for**




With #pragma omp **for**




https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop parallelism

Note that the **parallel do** and **parallel for** pragmas
do not create a team of threads:
they take the team of threads that is active,
and divide the loop iterations over them.

This means that the **omp for** or **omp do** directive
needs to be inside a **parallel region**.
It is also possible to have a combined
**omp parallel for** or **omp parallel do** directive.

If your parallel region only contains a loop,
you can combine the pragmas for the parallel region
and distribution of the loop iterations:

```
#pragma omp parallel for
  for (i=0; .....
```

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop parallelism

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```
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# Loop Schedules (1)

more **iterations** in a loop than **threads**
several ways to assign loop **iterations** to the **threads**
OpenMP lets you specify this with the **schedule clause**.

#pragma omp **for schedule**(....)

**Static schedules**
the **iterations** are assigned purely
based on the number of **iterations**
and the number of **threads**
(and the **chunk parameter**; see later).

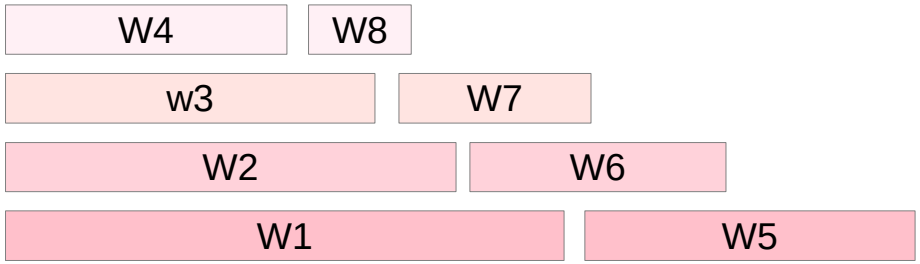
**Dynamic schedules**
**iterations** are assigned
to **threads** that are unoccupied.

when iterations take an unpredictable amount of time,
so **load balancing** is needed.

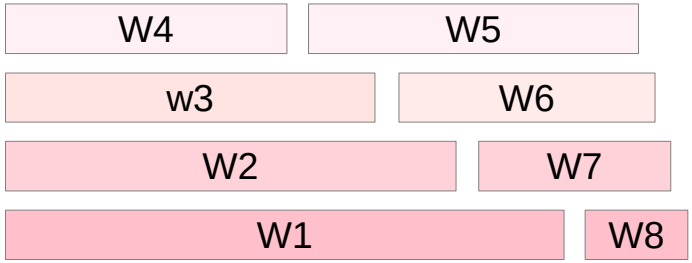
https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop Schedules (2)

**Static round robin scheduling**




**Dynamic scheduling**

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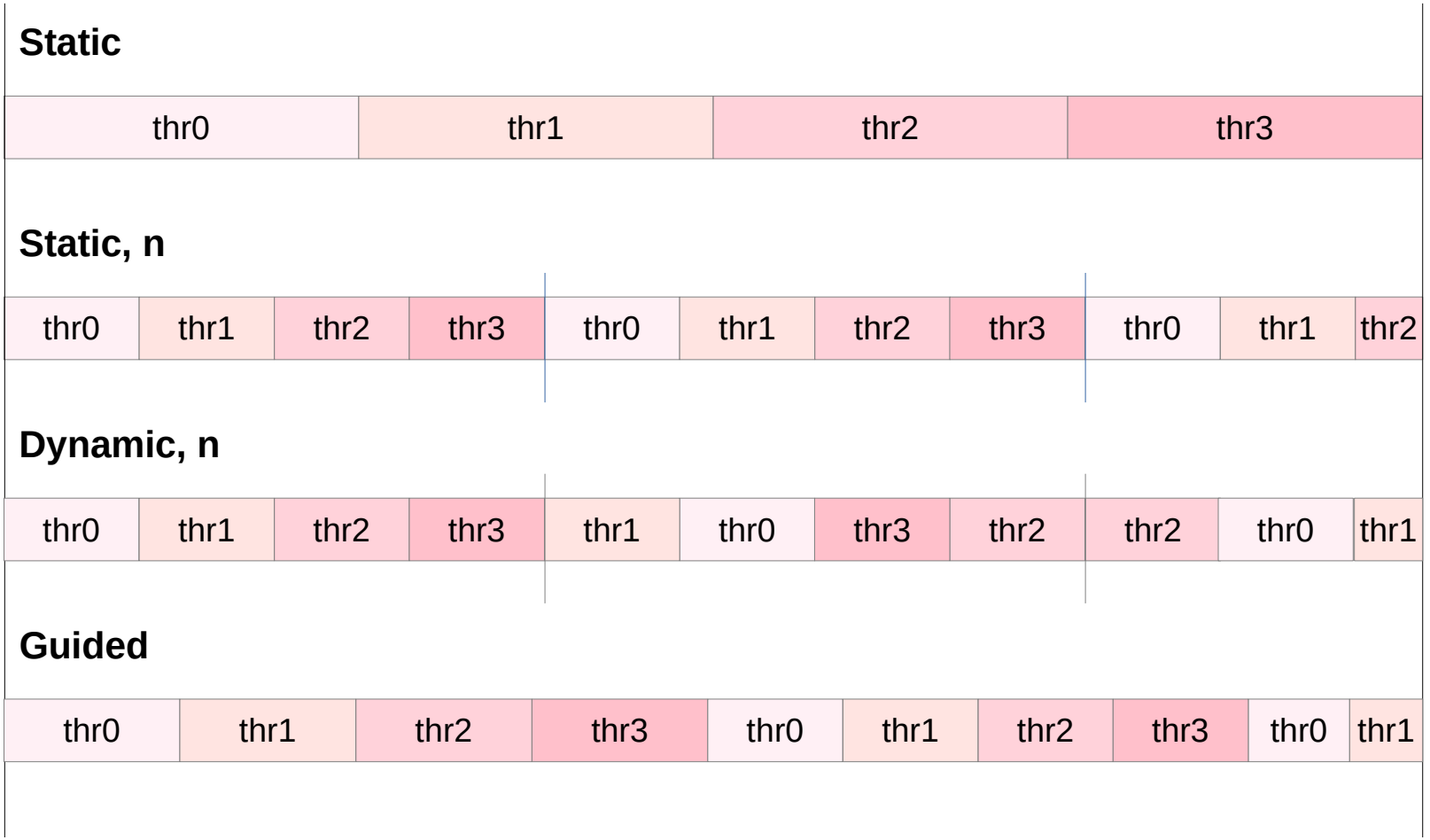
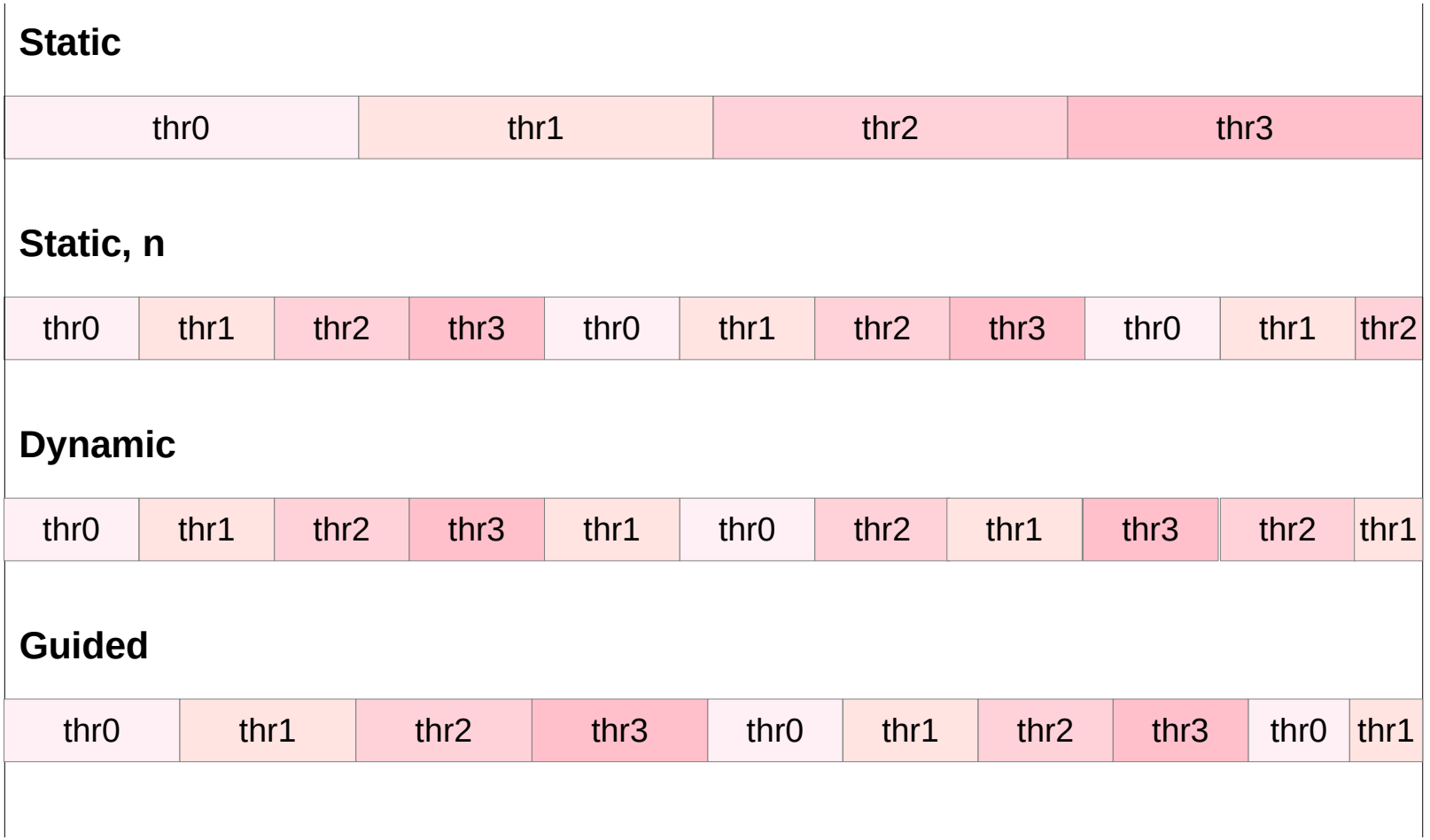
# Loop Schedules (3)




https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop Schedules (3)




https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop Schedules (4)

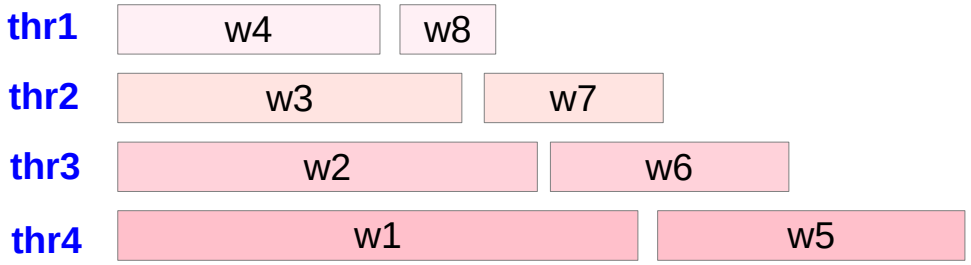
assume that each core gets assigned
two (blocks of) iterations and
these blocks take gradually
less and less time.

thread 1 gets two fairly long blocks,
whereas thread 4 gets two short blocks,

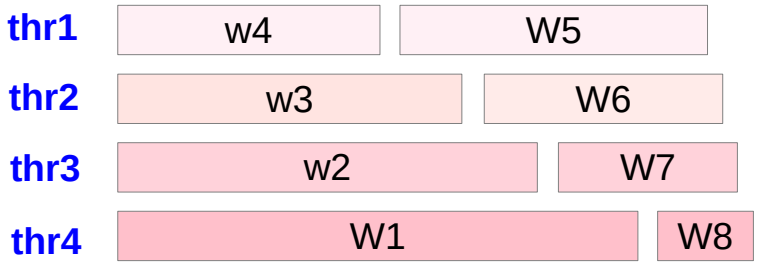
Thread 1 finishes much earlier.
**Imbalance** : unequal amounts of work

**load balancing**
thread 4 gets block 5,
since it finishes the first set of blocks early.
The effect is a perfect

**Static round robin scheduling**




**Dynamic scheduling**




https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop Schedule – Static (1)

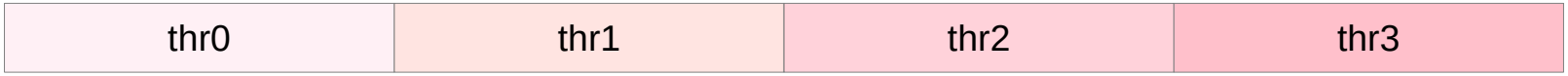
The **default static schedule** is
to assign one consecutive **block**
of **iterations** to each **thread**.

#pragma omp **for schedule(static)**
#pragma omp **for schedule(static, chunk)**

With **static scheduling**, the compiler
will split up the loop iterations at compile time,

When the iterations take roughly
the same amount of time,
this is the most efficient at runtime.

**Static**




https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

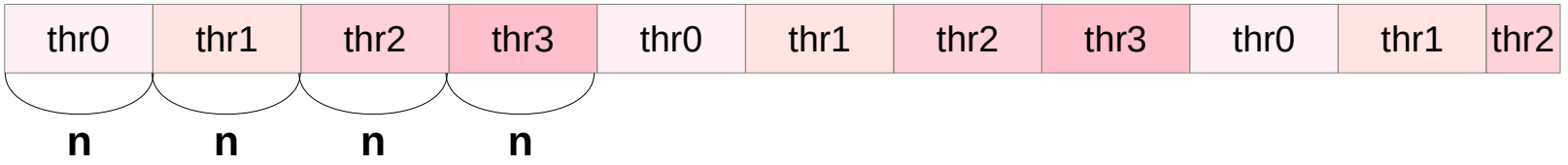
# Loop Schedule – Static (2)

#pragma omp **for schedule(static,chunk)**

If you want different sized blocks
you can defined a **chunk size chunk**

The choice of a **chunk size** is often
a balance between the **low overhead**
of having only a few chunks, (big chunks)
versus the **load balancing effect**
of having smaller chunks. (many chunks)

**Static, n**




https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop Schedule – Static (3)

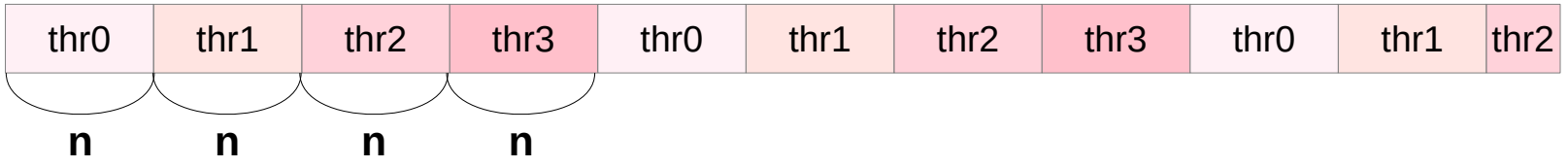
#pragma omp **for schedule(static,chunk)**

OpenMP divides the iterations
into chunks of size chunk-size

distributes the chunks to **threads**
in a circular order.

When no chunk-size is specified,
OpenMP divides iterations into chunks
that are approximately equal in size and
distributes at most one **chunk** to each **thread**.

**Static, n**




http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Static (4)

Static scheduling is used
when you know that each thread will do
the approximately same amount of work
at the **compile time**.

the following code can be parallelized
using OMP.  (assume only 4 threads)

```
float A[100][100];

for(int i = 0; i < 100; i++)
{
   for(int j = 0; j < 100; j++)
   {
      A[i][j] = 1.0f;
   }
}
```

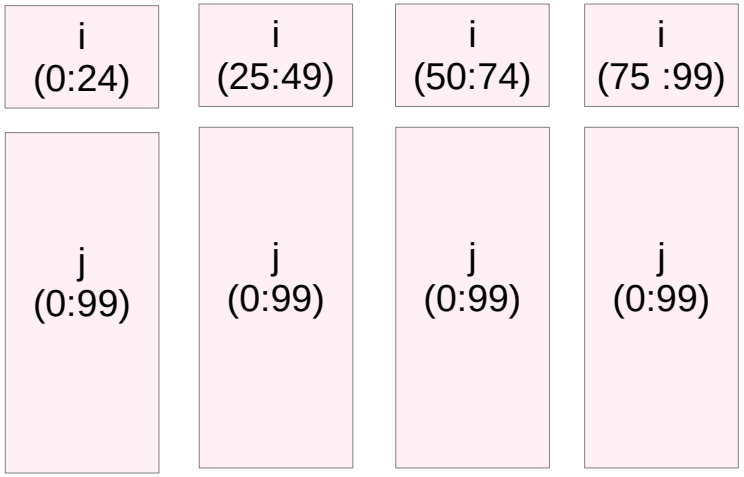
100 * 100 iterations
10000 / 4 iterations / thread

https://stackoverflow.com/questions/15508128/using-omp-schedule-with-pragma-omp-for-parallel-scheduleruntime

# Loop Schedule – Static (5)

```
float A[100][100];

#pragma omp for schedule(static)
for(int i = 0; i < 100; i++)
{
   for(int j = 0; j < 100; j++)
   {
      A[i][j] = 1.0f;
   }
}
```




to use the default static scheduling,
place pragma on the outer for loop,

then each thread will do
25% of the outer loop (i) work
and eqaul amount of inner loop (j) work

Hence, the total amount of work done
by each thread is same.

Hence, we could simply stick
with the default static scheduling
to give optimal load balancing.

https://stackoverflow.com/questions/15508128/using-omp-schedule-with-pragma-omp-for-parallel-scheduleruntime

# Loop Schedule – Static (6)

Assume : a for loop with 64 iterations and 4 threads

**schedule(static)**

OpenMP divides iterations into 4 chunks of size 16
and it distributes them to four threads.

64 iterations and 4 threads → 64 / 4 = 16

the 1st tread executes iterations 1, 2, 3, …, 15 and 16.

the 2nd thread executes iterations 17, 18, 19, …, 31, 32.

**schedule(static, 4)** and **schedule(static, 8)**

OpenMP divides iterations into chunks of size 4 and 8, respectively.

- when all iterations have the same computational cost.

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Static (6)

schedule**(static, 4)**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 16 | 17 | 18 | 19 | 32 | 33 | 34 | 35 | 48 | 49 | 50 | 51 |
| 4 | 5 | 6 | 7 | 20 | 21 | 22 | 23 | 36 | 37 | 38 | 39 | 52 | 53 | 54 | 55 |
| 8 | 9 | 10 | 11 | 24 | 25 | 26 | 27 | 40 | 41 | 42 | 43 | 56 | 57 | 58 | 59 |
| 12 | 13 | 14 | 15 | 28 | 29 | 30 | 31 | 44 | 45 | 46 | 47 | 60 | 61 | 62 | 63 |

schedule**(static, 8)**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 |
| 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 |
| 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

schedule**(static)**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

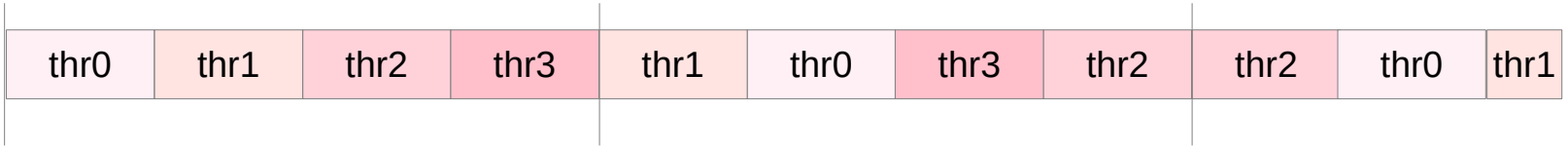
# Loop Schedule – Dynamic (1)

In **dynamic scheduling** OpenMP will
put **blocks** of iterations in a **task queue**,
(the **default chunk size** is **1**)
and the **threads** take one of these tasks
whenever they are finished with the previous.

#pragma omp **for schedule(dynamic[,chunk])**

While this schedule may give **good load balancing**
if the iterations take very differing amounts of time to execute,
it does carry **runtime overhead**
for managing the **queue** of iteration tasks.

**Dynamic**




arbitrary thread assignment

fixed chunk size except the last

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

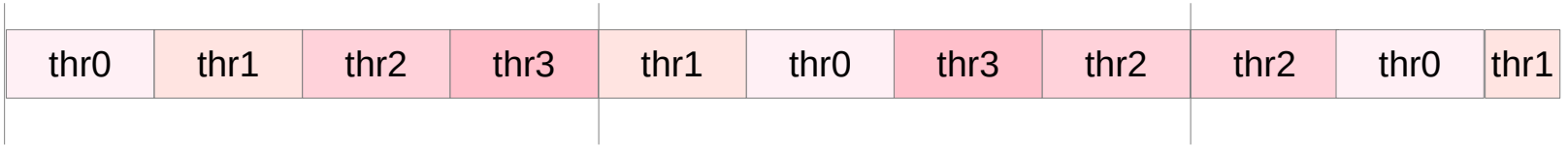
# Loop Schedule – Dynamic (2)

large **chunks** carry the least **overhead**,
but smaller chunks are better for **load balancing**.

If you don't want to decide on a schedule in your code,
you can specify the schedule will then **at runtime**
be read from the OMP_SCHEDULE environment variable.

You can even just leave it to the runtime library by specifying
**omp_set_schedule**.

**Dynamic**




arbitrary thread assignment

fixed chunk size except the last

https://pages.tacc.utexas.edu/~eijkhout/pcse/html/omp-loop.html

# Loop Schedule – Dynamic (3)

**for schedule(dynamic, chunk-size)**
the dynamic scheduling type

OpenMP divides the **iterations**
into chunks of size chunk-size.

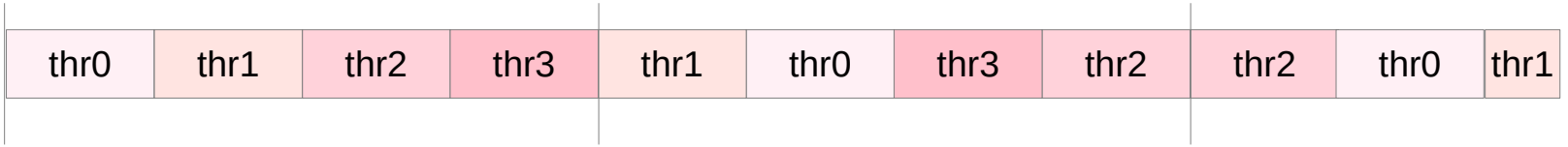
Each thread *executes*
a chunk of **iterations** and
then *requests* another chunk
until there are no more chunks available.

There is no particular order
in which the chunks are distributed
to the **threads**.

The order changes each time
when we execute the for loop.

If we do not specify **chunk-size**,
it defaults to one.

**Dynamic**




arbitrary thread assignment

fixed chunk size except the last

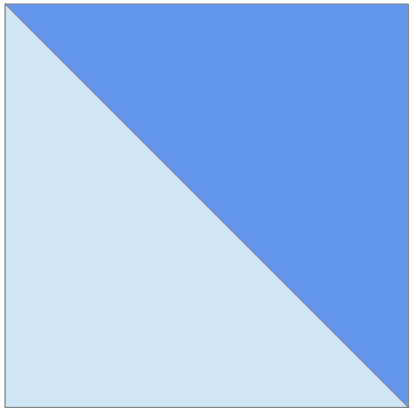
http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Dynamic (4)

**Dynamic scheduling** is used when you know that each thread will not do same amount of work by using **static scheduling**.

```
float A[100][100];

for(int i = 0; i < 100; i++)
{
   for(int j = 0; j < i; j++)
   {
      A[i][j] = 1.0f;
   }
}
```

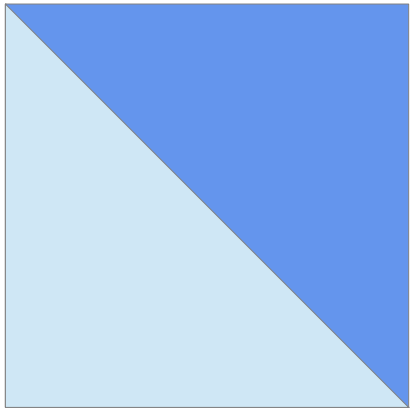


https://stackoverflow.com/questions/15508128/using-omp-schedule-with-pragma-omp-for-parallel-scheduleruntime

# Loop Schedule – Dynamic (5)

```
float A[100][100];

for(int i = 0; i < 100; i++)
{
   for(int j = 0; j < i; j++)
   {
      A[i][j] = 1.0f;
   }
}
```



The inner loop variable **j**
is dependent on the **i**.

the **default static scheduling**,

- the outer loop (i) work might be divided equally between the 4 threads,
- but the inner loop (j) work will be large for some threads.

- not equal amount of work
- not optimal **load balancing**

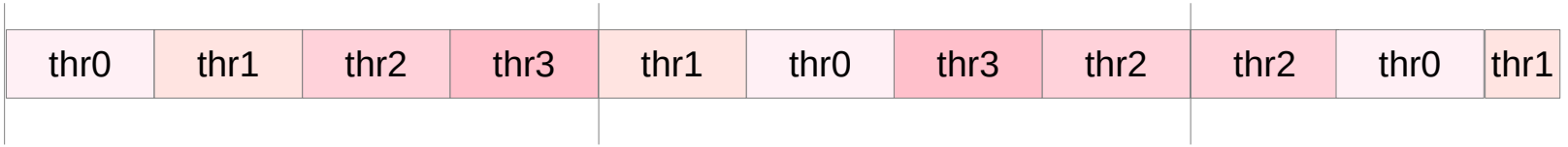
https://stackoverflow.com/questions/15508128/using-omp-schedule-with-pragma-omp-for-parallel-scheduleruntime

# Loop Schedule – Dynamic (6)

the dynamic scheduling is done at the run time
can make sure optimal **load balance**.

can specify the chunk_size for scheduling
which depends on the **loop size**.

**Dynamic**




arbitrary thread assignment

fixed chunk size except the last

https://stackoverflow.com/questions/15508128/using-omp-schedule-with-pragma-omp-for-parallel-scheduleruntime

# Loop Schedule – Dynamic (7)

**schedule(dynamic)** and **schedule(dynamic, 1)**
OpenMP determines similar scheduling.
the size of chunks is equal to **1** in both instances.

the distribution of chunks between the threads is arbitrary.

**schedule(dynamic, 4)** and **schedule(dynamic, 8)**
OpenMP divides iterations into chunks of size **4** and **8**, respectively.

the distribution of chunks to the threads has no pattern (abitrary)

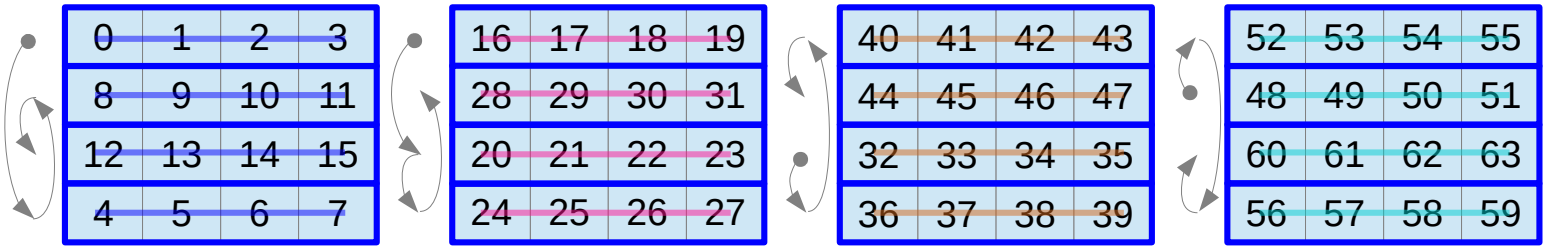
- when the iterations require different computational costs.
- when the iterations are poorly balanced between each other.

- higher **overhead** than the static scheduling type
  because it dynamically distributes the iterations during the runtime.

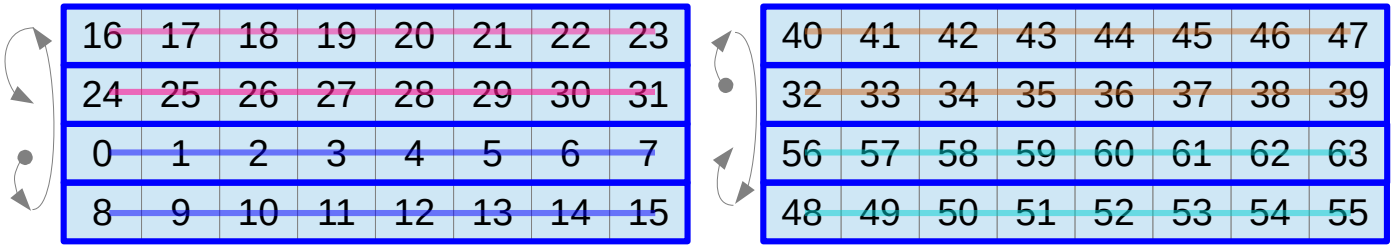
http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Dynamic (6)

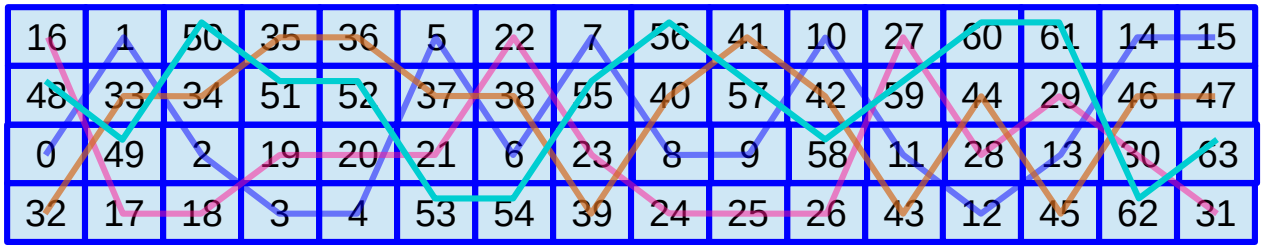
schedule**(dynamic, 4)**




schedule**(dynamic, 8)**




schedule**(dynamic)**




http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Guided (1)

The **guided** scheduling type is
similar to the **dynamic** scheduling type.

OpenMP again divides
the iterations into chunks.

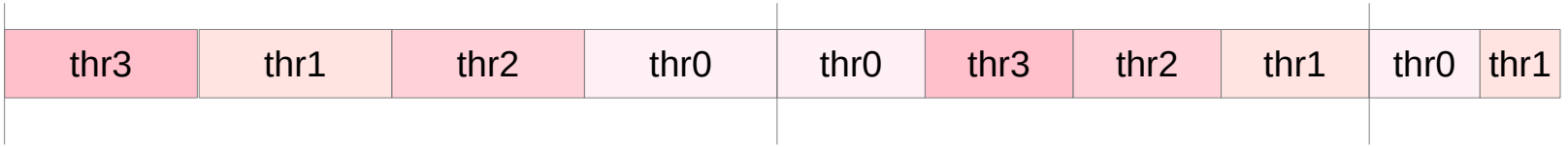
Each thread executes a chunk of iterations
and then requests another chunk
until there are no more chunks available.

The difference is in **the size of chunks**.

The size of a chunk is proportional
to the **number of unassigned iterations**
divided by the **number of the threads**.

Therefore **the size of the chunks**
decreases as the execution goes on

**Guided**




arbitrary thread assignment

decreasing chunk size

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Guided (2)

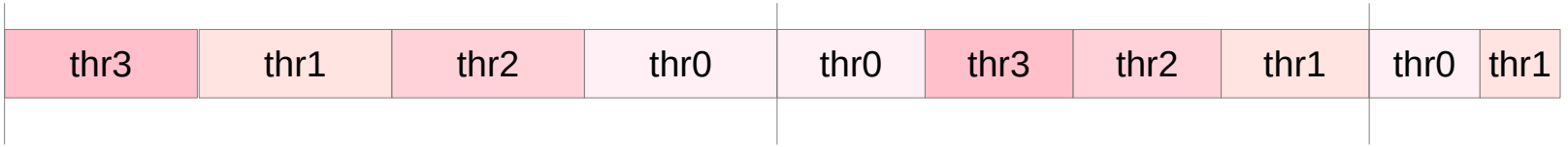
The **minimum size of a chunk**
is set by '**chunk-size'**
in the scheduling clause:

**for schedule(guided, chunk-size)**.

the chunk which contains the last iterations
may have smaller size than chunk-size.

If we do not specify **chunk-size**,
it defaults to **one**.

**Guided**




arbitrary thread assignment

decreasing chunk size

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Guided (3)

the **size** of the **chunks** is decreasing.

1st chunk has always 16 iterations. 64 iterations / 4 threads → 64 / 4 = 16

2nd chunk has always 12 iterations. (64-16) iterations / 4 threads → 48 / 4 = 12

3rd chunk has always 9 iterations. (48-12) iterations / 4 threads → 36 / 4 = 9

the **minimum chunk size** is determined in the schedule clause.
The only exception is the **last chunk**.
Its size might be lower then the prescribed minimum size.

The guided scheduling type is appropriate
when the iterations are poorly balanced between each other.

The initial chunks are larger, because they reduce overhead.
The smaller chunks fills the schedule towards the end of the computation
and improve load balancing.
This scheduling type is especially appropriate
when poor load balancing occurs toward the end of the computation.

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Guided (3)

schedule(guided)

| | |
|---|---|
| 64 | 64 / 4 = 16 |
| (64-16) | 48 / 4 = 12 |
| (48-12) | 36 / 4 = 9 |
| (36-9) | 27 / 4 = 7 |
| (27-7) | 20 / 4 = 5 |
| (20-5) | 15 / 4 = 4 |
| (15-4) | 11 / 4 = 3 |
| (11-3) | 8 / 4 = 2 |
| (8-2) | 6 / 4 = 2 |
| (6-2) | 4 / 4 = 1 |
| (4-1) | 3 / 4 = 1 |
| (3-1) | 2 / 4 = 1 |
| (2-1) | 1 / 4 = 1 |

schedule(guided, 4)

| | | |
|---|---|---|
| 64 | 64 / 4 = 16 | |
| (64-16) | 48 / 4 = 12 | |
| (48-12) | 36 / 4 = 9 | |
| (36-9) | 27 / 4 = 7 | |
| (27-7) | 20 / 4 = 5 | |
| (20-5) | 15 / 4 = 4 | |
| (15-4) | 11 / 4 = 3 | < 4 |
| (11-4) | 7 | 4 |
| (7-4) | 3 | 3 |
| (3-3) | 0 | |

schedule(guided, 8)

| | | |
|---|---|---|
| 64 | 64 / 4 = 16 | |
| (64-16) | 48 / 4 = 12 | |
| (48-12) | 36 / 4 = 9 | |
| (36-9) | 27 / 4 = 7 | < 8 |
| (27-8) | 19 | 8 |
| (19-8) | 11 | 8 |
| (11-8) | 3 | 3 |
| (3-3) | 0 | |

unassigned iterations / threads

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Static (6)

schedule**(static)**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

schedule(guided)

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 44 | 45 | 46 | 47 | 48 | 58 | 59 | 63 | | | | | | | | |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 49 | 50 | 51 | 52 | 60 | | | | | | | | | | | | | | | |
| 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 53 | 54 | 55 | 61 | | | | | | | | | | | | | | | | | | | |
| 37 | 38 | 39 | 40 | 41 | 42 | 43 | 56 | 57 | 62 | | | | | | | | | | | | | | | | | | | | | | |

| | |
|---|---|
| 64 | 64 / 4 = 16 |
| (64-16) | 48 / 4 = 12 |
| (48-12) | 36 / 4 = 9 |
| (36-9) | 27 / 4 = 7 |
| (27-7) | 20 / 4 = 5 |
| (20-5) | 15 / 4 = 4 |
| (15-4) | 11 / 4 = 3 |
| (11-3) | 8 / 4 = 2 |
| (8-2) | 6 / 4 = 2 |
| (6-2) | 4 / 4 = 1 |
| (4-1) | 3 / 4 = 1 |
| (3-1) | 2 / 4 = 1 |
| (2-1) | 1 / 4 = 1 |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 63 | | | | | | | | | | | | | | | |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 53 | 54 | 55 | 60 | | | | | | | | | | | | | | | | |
| 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 49 | 50 | 51 | 52 | 56 | 57 | 61 | | | | | | | | | | | | | | | | |
| 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 58 | 59 | 62 | | | | | | | | | | | | | | | | | |

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Static (6)

schedule**(static)**

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |

schedule(guided, 4)

| | | | | | | | | | | | | | | | | | | | | | < 4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 44 | 45 | 46 | 47 | 48 | 61 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 49 | 50 | 51 | 52 | 62 | | | | | |
| 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 53 | 54 | 55 | 56 | 63 | | | | | | | | |
| 37 | 38 | 39 | 40 | 41 | 42 | 43 | 57 | 58 | 59 | 60 | | | | | | | | | | | |

| | | |
|---|---|---|
| 64 | 64 / 4 = 16 | |
| (64-16) | 48 / 4 = 12 | |
| (48-12) | 36 / 4 = 9 | |
| (36-9) | 27 / 4 = 7 | |
| (27-7) | 20 / 4 = 5 | |
| (20-5) | 15 / 4 = 4 | |
| (15-4) | 11 / 4 = 3 | < 4 |
| (11-4) | 7 | 4 |
| (7-4) | 3 | 3 |
| (3-3) | 0 | |

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Auto

The auto scheduling type delegates
the decision of the scheduling
to the **compiler** and/or **runtime** system.

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedule – Runtime

The schedule(runtime) clause tells it
to set the schedule using the environment variable.

The environment variable can be set
to any other scheduling type.

It can be set by

setenv OMP_SCHEDULE “dynamic,5”

https://stackoverflow.com/questions/15508128/using-omp-schedule-with-pragma-omp-for-parallel-scheduleruntime

# Loop Schedules – Runtime

The **runtime** scheduling type defers
the decision about the scheduling
until the **runtime**.

different ways of specifying
the scheduling type in this case.

One option is with the environment variable
**OMP_SCHEDULE**

and the other option is
with the function
**omp_set_schedule**.

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Loop Schedules – Runtime

If the scheduling-type (in the schedule clause of the loop construct) is equal to runtime then OpenMP determines the scheduling by the internal control variable run-sched-var. We can set this variable by setting the environment variable OMP_SCHEDULE to the desired scheduling type. For example, in bash-like terminals, we can do

$ export OMP_SCHEDULE=sheduling-type

Another way to specify run-sched-var is to set it with omp_set_schedule function.

```
...
omp_set_schedule(sheduling-type);
...
```

http://jakascorner.com/blog/2016/06/omp-for-scheduling.html

# Nested Parallelism (1)

```
void fun1()
{
   for (int i=0; i<80; i++)
      ...
}

main()
{
  #pragma omp parallel
  {
    #pragma omp for
    for (int i=0; i<100; i++)
       ...

    #pragma omp for
    for (int i=0; i<10; i++)
       fun1();
  }
}
```

the 2nd loop in **main**
can only be distributed to 10 threads

80 loop iterations in **fun1**
which will be called 10 times in **main** loop.

total **800** iterations in **fun1** and the **main** loop

This gives much more parallelism potential
if parallelism can be added in both levels.

https://software.intel.com/content/www/us/en/develop/articles/exploit-nested-parallelism-with-openmp-tasking-model.html

# Nested Parallelism (2)

```
void fun1()
{
   #pragma omp parallel for
   for (int i=0; i<80; i++)
      ...
}

main
{
   #Pragma omp parallel
   {
      #pragma omp for
      for (int i=0; i<100; i++)
         …

      #pragma omp for
      for (int i=0; i<10; i++)
         fun1();
   }
}
```

may either have insufficient threads for the 1st main loop
as it has larger loop count, or

create exploded number of threads for the 2nd main loop
when OMP_NESTED=TRUE.

The simple solution is to split the parallel region in main and
create separate ones for each loop
with a distinct thread number specified.

https://software.intel.com/content/www/us/en/develop/articles/exploit-nested-parallelism-with-openmp-tasking-model.html

# Nested Parallelism (3)

```
void fun1()
{
   #pragma omp taskloop
   for (int I = 0; i<80; i++)
      ...
}

main
{
   #pragma omp parallel
   {
      #pragma omp for
      for (int i=0; i<100; i++)
         ...

      #pragma omp for
      for (int i=0; i<10; i++)
         fun1();
   }
}
```

don't have to worry about the thread number changes
in 1st and 2nd main loops.

Even though you still have a small amount of (10) threads
allocated for 2nd main loop,
the rest available threads will be able
to be distributed through omp **taskloop** in fun1.

https://software.intel.com/content/www/us/en/develop/articles/exploit-nested-parallelism-with-openmp-tasking-model.html

# Nested Parallelism (4)

**nested parallel regions** is
a way to distribute **tasks** by creating / forking more **threads**.

**parallel region** is the only construct
determines **execution thread number**
and controls **thread affinity**

Using **nested parallel regions** means
each **thread** in **parent region**
will yield multiple **threads** in enclosed regions,
which in turn create a product of **thread number**.

https://software.intel.com/content/www/us/en/develop/articles/exploit-nested-parallelism-with-openmp-tasking-model.html

# Nested Parallelism (5)

**omp tasking** shows another way
to explore parallelism by adding
more **tasks**, instead of **threads**.

though the **thread number** is unchanged
as specified at the entry of the **parallel region**,
the increased **tasks** from the **nested tasking** constructs
can be distributed and executed by any available/idle **threads**
in the current team of the same parallel region.

This gives opportunities to fully use all threads' capability,
and improve balance of workloads automatically.

https://software.intel.com/content/www/us/en/develop/articles/exploit-nested-parallelism-with-openmp-tasking-model.html

# Implicit task (1)

In addition to **explicit tasks** specified using the **task** directive,
the OpenMP specification version 3.0 introduces
the notion of **implicit tasks**.

An **implicit task** is a task generated
- by the **implicit parallel region**,
- when a **parallel construct** is encountered during execution.

The **code** for each **implicit task** is
the code inside the **parallel construct**.

Each **implicit task** is
- assigned to a different **thread** in the **team** and is **tied**;
- always executed from beginning to end
by the **thread** to which it is initially assigned.

https://docs.oracle.com/cd/E19205-01/820-7883/6nj43o69j/index.html

# Implicit task (2)

All **implicit tasks** generated
when a **parallel construct** is encountered
are guaranteed to be complete
when the **master thread** exits the **implicit barrier**
at the end of the **parallel region**.

all **explicit tasks** generated within a **parallel region**
are guaranteed to be complete
on exit from the next **implicit** or **explicit barrier**
within the **parallel region**.

https://docs.oracle.com/cd/E19205-01/820-7883/6nj43o69j/index.html

# Implicit task (3)

When an **if clause** is present on a **task construct**
and the value of the scalar-expression evaluates to false,
the thread that encounters the task must immediately execute the task.

The **if clause** can be used to avoid the **overhead** of
generating many **finely grained tasks** and
placing them in the **conceptual pool**.

https://docs.oracle.com/cd/E19205-01/820-7883/6nj43o69j/index.html

# Implicit barrier

Implicit BarriersSeveral OpenMP* constructs have implicit barriers

- parallel
- for
- single

Unnecessary barriers hurt performance

- Waiting threads accomplish no work!

Waiting threads accomplish no work!
Suppress implicit barriers, when safe, with the nowait

https://www.intel.com/content/dam/www/public/apac/xa/en/pdfs/ssg/Programming_with_OpenMP-Linux.pdf

## References

[1] en.wikipedia.org
[2] M Harris, http://beowulf.lcs.mit.edu/18.337-2008/lectslides/scan.pdf